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Comparison of Flow Dynamics and Bifurcation Angles in Tributary and Distributary Channel Networks

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Abstract

The dynamics of channel mouth bifurcations on river deltas can be understood using theory developed in tributary channel networks. Bifurcations in groundwater-fed tributary networks have been shown to evolve dependent on diffusive groundwater flow patterns directly adjacent to the channel network, producing a critical angle of 72°. We test the hypothesis that bifurcation angles in distributary channel networks are likewise dictated by a diffusive external flow field, in this case the shallow surface water surrounding the subaqueous portion of distributary channels in a deltaic setting. We measured 25 unique distributary bifurcations in an experimental delta and 197 bifurcations in 10 natural deltas, yielding a mean angle of $70.4\,^{\circ} \pm 2.6\,^{\circ}$ (95% confidence interval) for natural field-scale deltas and a mean angle of $68.3\,^{\circ} \pm 8.7\,^{\circ}$ for the experimental delta, consistent with the theoretical prediction. Further analysis shows that angles cluster around the critical angle over small measurement length-scales relative to channel width, even at the moment that channel bifurcations initiate. Distributary channel bifurcations are important features in both modern systems, where the channels control water, sediment, and nutrient routing, and in river delta stratigraphy, where the channel networks can dictate large-scale stratigraphic heterogeneity. Although distributary networks do not mirror tributary networks perfectly, the similar control and expression of bifurcation angles suggests that additional morphodynamic insight may be gained from further comparative study.

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1 Introduction

Branching channel networks are a classic example of pattern formation arising from self-organization in the natural environment [1, 2, 3, 4, 5], forming the primary pathways for sediment accumulation and dispersal on planetary surfaces. Their dendritic structure can cover continents in the case of tributary systems, and set large scale depositional patterns in river delta and deep water distributary systems. Hence, our understanding of channel network dynamics is critical to the study of planetary science, landscape evolution, source-to-sink sediment routing, coastal sustainability, fluvial-deltaic and deep-water stratigraphy, and basin analysis.

The topology of both distributary and tributary channel networks prominently features channel bifurcations [6, 7, 8, 9, 10], or confluences in a tributary setting. In the context of distributary networks, channel bifurcations are defined as distinct divisions of channelized flow, where a single channel, referred to as the parent channel, branches into two or more channels, referred to as daughter channels. The daughter channels are separated by a bar, island, or shallow bay where sediment transport is significantly reduced or non-existent, and any flow is unchannelized. This study focuses on bifurcations that initiate near the distal end of the network, excluding partial avulsions that cause new bifurcations to form on the established network [11].

Despite the dendritic similarity between tributary and distributary networks, the scientific understanding of these systems has developed independently. Fluvial tributary networks have been modeled for over a century as the subset of a landscape where there is sufficient shear stress imparted by a flow to transport sediment via fluvial processes [12, 13, 14, 15]. Recent studies have advanced the theory to show that tributary networks are partially [16, 17, 10] or completely [18, 19, 20, 21, 22] controlled by diffusive transport of fluid and/or sediment outside of the channel network. Distributary channel networks, on the other hand, have been understood as the product of sedimentation from turbulent jets that form at the mouths of rivers entering basins [23, 24, 25, 26, 3]. Emergent network scales in distributary settings have been linked to the distance from a channel mouth to the locus of mouth bar aggradation, which in turn is linked to aspects of channelized flow at a river mouth: inflow buoyancy and inertia, bed friction, the width-to-depth ratio of the channel, and sediment characteristics [25, 27, 24, 28, 3]. Given the general dendritic similarity of tributary and distributary networks, we find it inconsistent that tributary network structure would depend on flow outside of the network and that distributary networks would depend on aspects of flow within the network.

We make a case for unchannelized flow patterns controlling distributary network structure by analyzing the angle of bifurcation in deltaic distributary networks. Recent studies of a tributary channel network excavated by groundwater-seepage-driven erosion in Florida [20] has shown the presence of a characteristic channel bifurcation angle of 72° that arises from diffusive groundwater flow in proximity to incipient channel bifurcations. When the population of tributary bifurcation angles found in a network are measured, this critical angle emerges as the mean angle, albeit with a significant standard deviation. While this finding is a remarkable advancement, questions about the critical angle remain. First, the spatial scales where the critical bifurcation angle is valid are predicted to be small [20], but remain untested. Second, the slowly evolving field-scale network prevents the observation of angles over time, leaving the hypothesis that incipient channels evolve toward the critical angle also untested. The dependence of bifurcation angle on measurement length-scale and time are essential for predicting the emergent dynamics of networks.

In this study, we show that unchannelized surface flow in the presence of an incipient distributary bifurcation can also be modeled as diffusive flow, and justify this approach by showing that distributary channel networks found in experimental and field scale river deltas also exhibit a mean bifurcation angle consistent with the 72° prediction. Further, the data allow the valid spatial scales to be assessed and temporal evolution of bifurcations to be analyzed. We conclude that at the scale of individual bifurcations, dynamics of tributary and distributary networks are similar despite the obvious difference of reversed flow direction with respect to the bifurcation.

2 Theory

Devauchelle et al. [2012] (hereafter referred to as DPSR12) established that in tributary networks incised by groundwater seepage erosion, the angle of tributary bifurcations is controlled by the groundwater flow field directly outside the channel network. The height of the water table in the groundwater flow field (h) above a horizontal, impermeable layer in isotropic media is a solution of the Poisson equation [21, 20, 29, 22, 30]:

$$\nabla^2 h^2 = -\frac{2P}{K}, \tag{2.1}$$

where K is hydraulic conductivity (L/T) and P is rate of precipitation (L/T). In close proximity to a channel, P is negligible relative to horizontal groundwater flux, which integrates precipitation over an entire basin [21]. This means that P can be disregarded, allowing the height of the groundwater flow field outside of the channel network to be modeled as a function of the Laplace equation:

$$\nabla^2 h^2 = 0. \tag{2.2}$$

The water surface around an incipient bifurcation is then modeled according to equation (2.2), with boundary conditions imposed at the channel network. Assuming that channels extend in the direction from which flow enters the channel tip, the growth of the incipient daughter channels is likewise related to equation (2.2). When the incipient angle between the daughter channels is small, channel tips grow away from each other, causing the angle of the developing bifurcation to increase. When the incipient angle is large, the channel tips curve toward one another, reducing the developing bifurcation angle. When the bifurcation angle is $\alpha = 72\,^\circ$, the plan-view flow path entering the daughter channel tips approaches the tips with no curvature, and thus the bifurcation angle does not change as it grows. Hence, a critical angle of $\alpha_{cr} = 72\,^{\circ}$ represents a stable morphology for the bifurcation as it grows in a diffusive groundwater field. The derivation of α_{cr} assumes symmetry across the axis of the parent channel, which means that the incipient daughter channels are identical in their ability to carry seepage flow. We refer the reader to Devauchelle et al. [2012] and Petroff et al. [2013] for detailed derivations of α_{cr}. DPSR12 validated this prediction with 4,966 bifurcations measured in a natural seepage tributary network in Florida, USA, which showed a mean characteristic angle of $71.98\,^{\circ} \pm 0.88\,^{\circ}$ (95% confidence interval), consistent with the theoretical prediction of α_{cr}. Because the critical bifurcation angle was predicted strictly from flow outside the channel, the channel network in these environments is a function of flow outside the channel network.

It is important to note that these reductive equations assume steady-state conditions, which allow for the physical components of the system (such as hydraulic conductivity) to be disregarded. In a system that is not in steady-state conditions, the underlying assumptions do not apply and the height of the water table would not be a solution of equation (2.2).

The flow patterns in surface water outside of distributary channels behaves similarly to the groundwater flow patterns in seepage networks. Theory developed by DPSR12 shows that a critical angle of $72\,^{\circ}$ is dependent on two assumptions: that (a) channels grow forward in the direction from which water enters them, and that (b) flow outside of the channel network can be described by the Laplace equation. Here, we will show that it is valid to assume diffusive flow patterns in the unchannelized region of distributary networks that are hydrologically connected to the channel. Then, we will argue that distributary channel network extension occurs in the direction in which flow leaves the channel tips (Figure 2.1). Together, these assumptions predict the existence of a congruent critical angle for tributary and distributary channel network bifurcations.

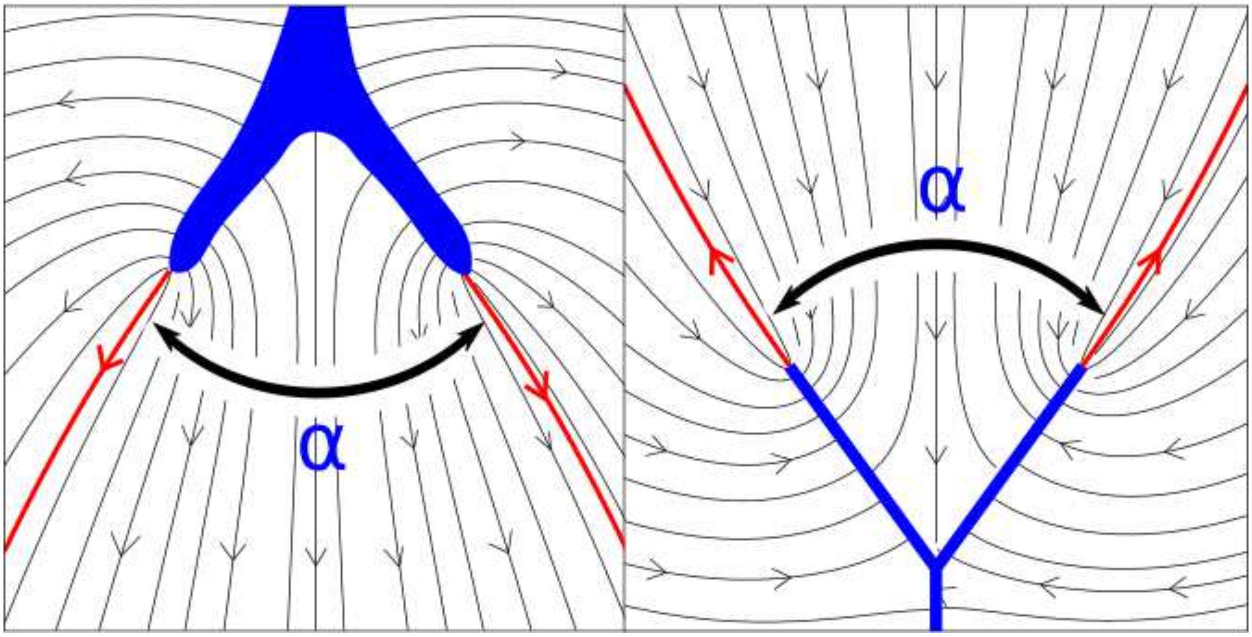

Figure 2.1: **Conceptual diagram of external flow fields.** Black flowlines indicate the external flow direction field $\left(\hat{d}\right)$ in tributary channel networks (right, figure modified from DPSR12) and distributary channel networks (left). Red lines indicate direction of channel tip growth. The dynamics of the external flow field in both networks define the critical angle of bifurcation, α_{cr}.

In order for diffusive flow to exist outside of distributary networks, there must be a connection between distributary channels and inter-distributary bays. Recent work on the Wax Lake Delta (WLD, Figure 3.1A), a $\sim$100 km^2 river delta in coastal Louisiana with many bifurcations, shows that its distributary channels are hydraulically connected to inter-distributary bays via flow over subaqueous levees and through many small tie-channels [31, 32, 33]. This hydraulic connectivity allows significant amounts of water to depart channels laterally, and travel through the delta as unchannelized flow. While most analysis of deltaic channel-interchannel exchange has been done on the WLD [31, 32], it is likely to be the rule rather than the exception for actively building natural deltas: all deltaic deposition occurs subaqueously, meaning that water must cover the actively growing portion of a delta with some recurrence. During these flooded conditions, pathways connecting the distributary channel network and unchannelized regions of islands are present.

Further measurement of the WLD shows that channels extend from their downstream tips via erosion of delta front sediments [34]. Channel extension was observed primarily during periods of low river flow when tidal reworking of the deposit was dominant. The direction of channel extension occurred in the direction that flow departed channel tips [31]. If channels can be assumed to extend along the flow path from which flow departs channel tips, and this flow path can be modeled, then a characteristic bifurcation can be found using methods similar to DPSR12.

Flow in surface water directly outside of salt marshes and tidal flats has also been shown to be diffusive [35], assuming steady-state conditions and friction-dominated flow across the shallow salt marsh. While the river deltas studied here are constructed through primarily fluvial processes, the flow field outside of the channel network in the inter-distributary bay can be conceptualized using the same theory. Rinaldo et al. [1999] utilized dimensionless parameters for inertia (S) and friction (R) relative to local effect of gravity in the tidal flat in order to transform conservation of momentum equations into a modified form of the Poisson equation solving for the water surface elevation. The derivation for the Laplacian equation describing flow in tidal flats begins with the Boussinesq approximation in a 2D plane:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = -g\frac{\partial \eta}{\partial x} - g\frac{U}{C^2 D}\sqrt{U^2+V^2}, \tag{2.3}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -g\frac{\partial \eta}{\partial y} - g\frac{V}{C^2 D}\sqrt{U^2+V^2}, \tag{2.4}$$

$$\frac{\partial}{\partial x}(DU) + \frac{\partial}{\partial y}(DV) + \frac{\partial D}{\partial T} = 0, \tag{2.5}$$

where U and V represent depth-averaged flow velocities in the x- and y-directions, respectively, η represents water surface height relative to mean sea level, t represents time, D represents flow depth, C is the Chezy coefficient, and g is the gravity constant. The equations for the Boussinesq approximation in a 2D plane (equations 2.3, 2.4, 2.5) are then converted in order to make the physical quantities dimensionless by multiplying each term by a dimensionless parameter. The dimensionless inertia factor, S, is defined as follows:

$$S = \frac{\omega U_0 L_0}{g a_0}, \tag{2.6}$$

where ω is tidal frequency, U_0 is characteristic depth-averaged flow velocity, L_0 is a characteristic spatial scale, g is the gravitational constant, and a_0 is the characteristic scale of difference in water surface elevation between channels and watershed divides for tidal flats. R is defined as follows:

$$R = \frac{{U_0}^2 L_0}{C^2 D_0 a_0}, \tag{2.7}$$

where C is the Chezy coefficient and D_0 is a characteristic maximum flow depth.

The ratio of S/R can be used to indicate the relative influence of friction- or inertia-dominated flows. If S/R is much less than 1, we assume that local flow is friction-dominated, or in other words the friction scales are much larger than the inertia scales. Here we demonstrate that flow in the inter-distributary bays on the Wax Lake Delta is friction-dominated. S/R can be represented as:

$$S/R = (C^2 D_0 \omega)/(g U_0). \tag{2.8}$$

We assume characteristic values for these variables on the Wax Lake Delta, which functions as an analog for all fluvial deltas. Chezy coefficient values range from 50-100, mean flow depth in the inter-distributary bay is approximately 0.1 meters, ω for the WLD region of the Gulf of Mexico is $216,000^{-1}$ seconds^{-1} (e.g. the frequency of a 6-hour tidal period), and U_0 is approximately 0.1 m/s [31], giving a S/R value of approximately 0.03 for the inter-distributary bays of the Wax Lake Delta, meaning that flow in those regions is friction-dominated, therefore the following Laplace equations derived in Rinaldo et al. [1999] for flow in tidal flats additionally apply to the inter-distributary bays of the Wax Lake delta. It is important to note that *channelized* flow in the Wax Lake Delta can be inertia-dominated or friction-dominated - the S/R value is specifically derived for unchannelized inter-distributary bays, and all work that follows is independent of channelized flow.

Based on the above equations, Rinaldo et al. [1999] simplified the standard Boussinesq approximations for conservation of momentum in a two-dimensional field, and showed that for flat, unchannelized areas that were hydraulically connected to channels and that were small relative to the tidal wavelength, the water surface elevation within the unchannelized portions of these systems could be simplified to a solution of the Poisson equation:

$$\nabla^2 \eta_1 = \frac{\Lambda}{(\eta_0 - z_{\mathrm{b}})^2} \frac{\partial \eta_0}{\partial t}, \tag{2.9}$$

where η_1 is the local water surface elevation above the average tidal elevation on the salt marsh (η_0) at time t, and z_{b} is the elevation of a flat, uniform salt marsh bottom. Using terms relevant to the inter-distributary bay region of a river delta, we represent this equation as follows:

$$\nabla^2 h = \frac{\Lambda}{h^2} \frac{\partial h}{\partial t}, \tag{2.10}$$

where h is the elevation of the water surface above the flat, unchannelized bed and Λ is a dimensionless friction coefficient (¡1). Similar to precipitation in seepage networks, shown in equations (2.1) and (2.2), the magnitude of vertical flux associated with tidal range ($\frac{\partial h}{\partial t} < 10^{-5}$m/s) is small relative to horizontal flow velocities ($\sim 10^{-1}$ m/s), meaning that $\frac{\partial h}{\partial t}$ can be neglected assuming steady-state conditions and friction-dominated flow, yielding:

$$\nabla^2 h \ = 0. \tag{2.11}$$

Therefore groundwater in the vicinity of a seepage channel (equation (2.2)) and surface water in the vicinity of a delta or marsh channel (equation (2.11)) can both be described by the Laplace equation when in steady-state conditions, albeit with the h raised to a different exponent in each case. However, the h exponent is inconsequential for predicting channel extension direction, as equations (2.2) and (2.11) produce the same flow direction field. Flow direction is the unit vector of the gradient $\hat{d} = \frac{\nabla h}{|\nabla h|}$ (Figure 2.1), and $\frac{\nabla h^2}{|\nabla h^2|} = \frac{2h\nabla h}{|2h\nabla h|} = \frac{2h\nabla h}{2h|\nabla h|} = \frac{\nabla h}{|\nabla h|}$. Hence, if the boundary conditions set by the channels are the same, the flow magnitudes (speed) will be different between the two systems, but the flow directions traced by groundwater flow and distributary surface water will be similar. Since the direction of channel extension is assumed to be controlled by the flow direction into a channel tip, the similarity in flow direction fields should be sufficient to produce congruent critical bifurcation angles in tributary and distributary environments.

3 Methods

We test for the presence of a critical angle $\alpha_{cr} = 72^\circ$ in distributary channel bifurcations using measurements from field- and laboratory-scale deltas (Figure 3.1). Field-scale deltas possess complex bifurcation geometries, but evolve too slowly to measure significant evolution. Laboratory scale deltas have relatively simple geometries, yet their evolution can be tracked in time. Together, they provide data for investigating a critical angle of bifurcation, as well as its spatial and temporal variability.

We analyzed bifurcations of the Atchafalaya, Colville, Danube, Dnepr, Don, Laitaure, Mossy, Parana, Pechora, and Wax Lake deltas (Figure 3.1). This selection of deltas was chosen based on minimal influence from wave, tide and anthropogenic forces, and on the wide variety of climates, ecological environments, and water discharges found in the depositional settings of each of the deltas [25]. Distributary channel bifurcation angles were traced from aerial imagery of each delta. These deltas roughly follow the traditional morphological footprint of fluvial-dominated digitate deltas, with distinct channels bifurcating and branching out from a single trunk channel [25].

Bifurcation angle measurements (α) were made using ImageJ, an open-source image analysis software (https://imagej.nih.gov/ij/). The angle is defined as $\alpha = \angle ABC$, where B is placed at the apex of the island and A and C are placed some linear distance L down the island flanks (Figure 3.2). The application of diffusive flow within islands is scale dependent, so we chose L as a function of the parent channel width (W_0) directly upstream of the bifurcation. Our primary analyses were performed on angles where $L/W_0 = 1$. However, we also varied L/W_0 to determine the importance of measurement length-scale on bifurcation

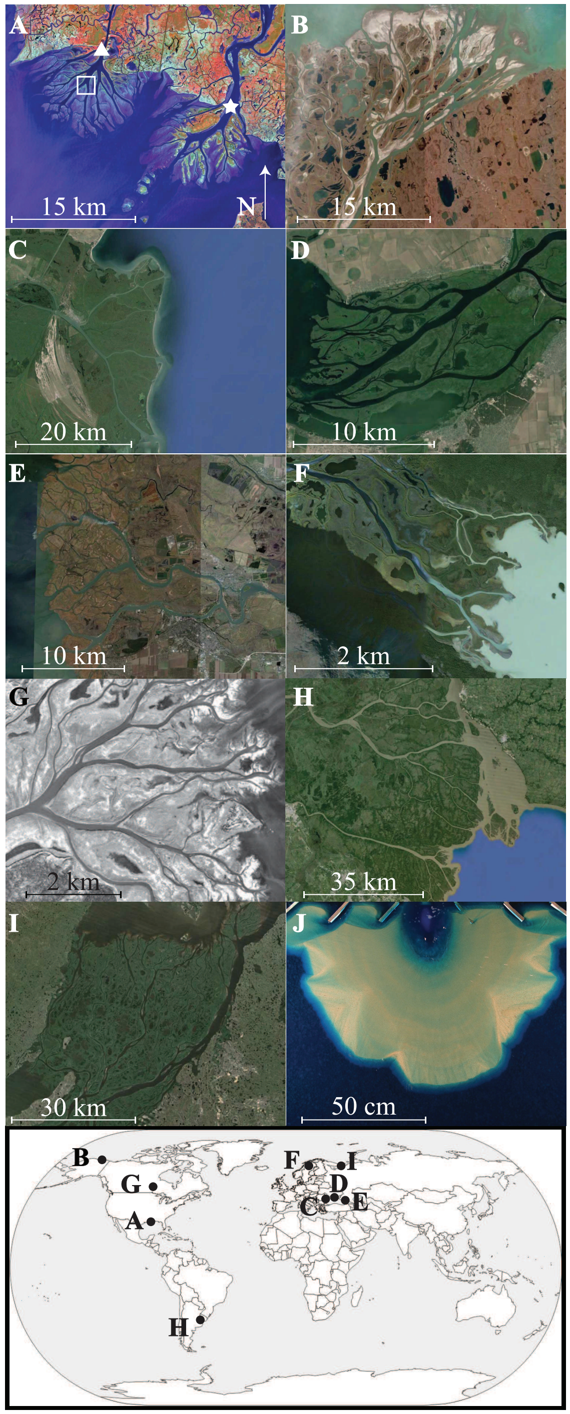

Figure 3.1: **Delta images used for this study.** All images of field-scale deltas shown are the images used for data collection. A time series of experimental delta images was used in data collection. From top to bottom, Atchafalaya and WLD (A, respectively indicated by the star and triangle), Colville (B), Danube (C), Dnepr (D), Don (E), Laitaure (F), Mossy (G, ref. Edmonds and Slingerland [2007]), Parana (H), Pechora (I), and the experimental delta (J). World map icons approximately correspond to field-scale delta locations. White square in (A) represents the approximate location of Fig. 3.2. (Image Source: Google Earth)

angle.

Bifurcations in which one of the daughter channels displayed a width narrower than 20% of the width of the opposite channel were not measured. This criterion excludes extremely asymmetric bifurcations from our measurements. This is done because the derivation of α_{cr} implicitly assumes symmetric daughter channels. However, the criterion includes slightly asymmetric bifurcations which are common in nature [36].

The experimental dataset was measured from delta-building experiment WY-9 conducted at the University of Wyoming. During the experiment, water and sediment composed of well-sorted medium-grained sand entered an enclosed basin through a pipe directly beneath base level, which was held constant during the experiments. A fluid discharge of 18 L/min and a sediment discharge of 0.05 L/min was used. The experiment spontaneously produced many islands that migrated laterally and downstream, forming a distributary network. Islands and their associated bifurcations were removed when they were either eroded away or merged with a neighboring island due to sedimentation in the intervening channel.

Populations of bifurcation angles were compared to α_{cr} to test for consistency with the DPSR12 model that indicated bifurcation angle is controlled by diffusive flow patterns outside of the channel network. It was assumed that individual bifurcation angles were sampled from a normal distribution with some mean μ and standard deviation σ. Bifurcations measured on all field-scale deltas were combined into a single population because individual field-scale deltas do not contain sufficient bifurcations to resolve emergent behavior. If $\mu = \alpha_{cr}$ for all deltas, then the combined population would also have a mean equal to α_{cr}, regardless of whether σ varied between deltas. Conversely, if $\mu \neq \alpha_{cr}$ for all deltas, then it is unlikely the mean of the combined population will show a mean of approximately 72°.

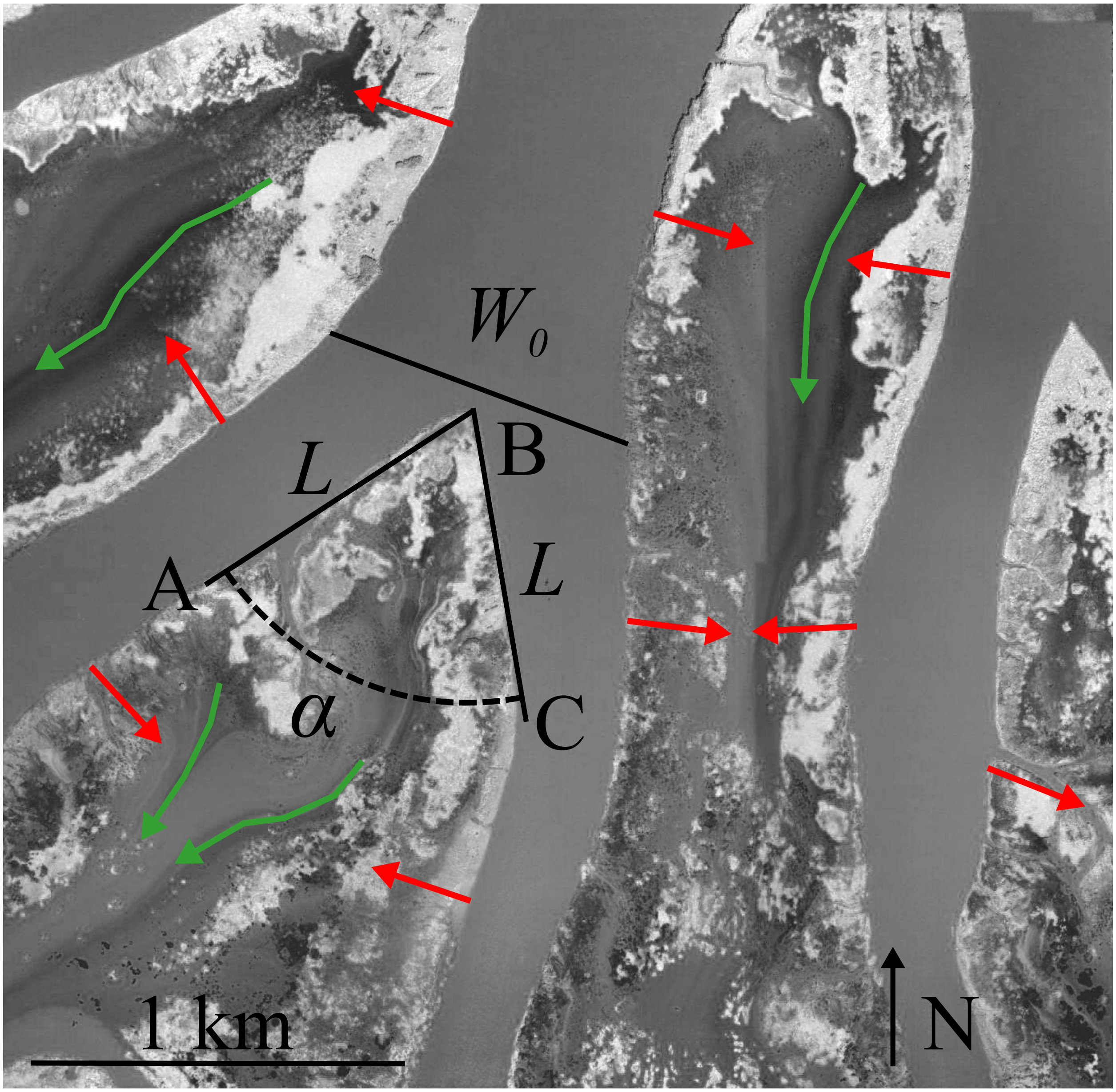

Figure 3.2: **Method of bifurcation angle measurement on the Wax Lake delta.** See Figure 3.1A for location. W_0 indicates channel width directly upstream of bifurcation. The bifurcation angle, α, is measured using limb lengths L equal to one normalized channel length (or one channel width, $L/W_0 = 1$) downstream of the bifurcation, shown in the figure as $\angle ABC$. Flow path of unchannelized water departing the channel is indicated with red arrows. Note how external flow patterns (traced by green arrows along the streaklines) compare to schematic flow patterns in Figure 2.1. (Image Source: USGS Landsat)

Experimental bifurcations were measured over time, but only the first measurement from each bifurcation was used in a test to ensure measurement independence. This meant that the population contained angles measured at different times during the experiment, unlike the field measurements.

In order to study the behavior of distributary channel bifurcations over both spatial and temporal scales, the angle of bifurcation was measured as a function of normalized channel length (see 'Methods', paragraph 3, and Figure 3.2) and as a function of time elapsed since formation of bifurcation. Because we could not observe field-scale deltas over a meaningful time interval, and because the experimental deltas form very short channels relative to their width, we elected to utilize angles from the WLD (Figure 3.1A) for spatial analysis and the experimental delta for temporal analysis of bifurcation angle. Bifurcation angle was measured with L/W_0 ranging from 0.25 to 16 for each major bifurcation on the WLD. In the experiment, bifurcation angle was measured at 30 second time increments to a limit of 450 seconds - although some bifurcations were extant for nearly half of the experiment, α was only analyzed when there were sufficient ($n > 25$) measurements.

To examine whether distributary channel bifurcations exhibited a critical bifurcation angle, the multiple-mean method was used to estimate the 95% confidence interval of the mean of the distribution (μ) [37]. If the 95% confidence interval of μ overlapped α_{cr}, then the sample was determined to be consistent with a critical angle and diffusive flow patterns could be considered the likely control on the bifurcation angle. If the range of μ did not include α_{cr}, then the hypothesis of diffusive flow was deemed inconsistent. This analysis is not a statistical test of whether $\mu = \alpha_{cr}$, but provides an objective method for comparing natural systems that exhibit variability to the theoretical prediction [20].

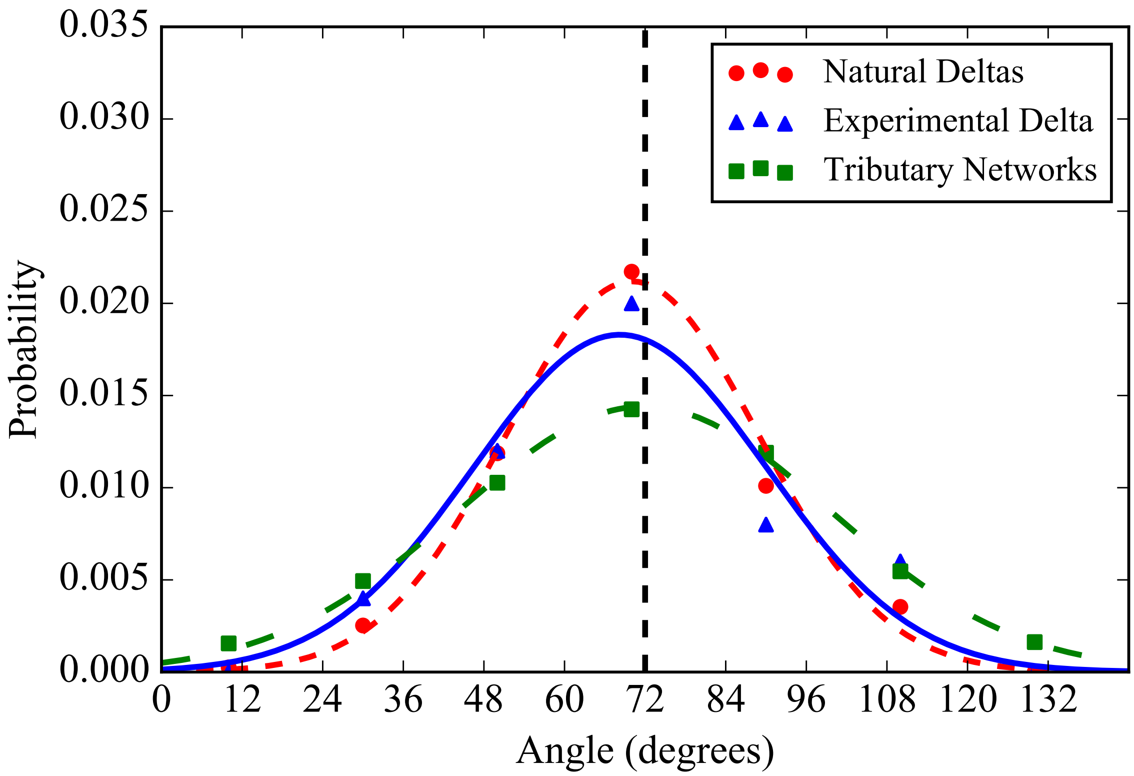

Figure 4.1: **Histogram and probability density function of bifurcation angles for distributary channels measured in our study and tributary channels measured in Devauchelle et al. [2012].** Vertical line marks the mathematically determined critical angle of 72°. Bin size is 20°. Solid line represents experimental data, short dashes represent the field-scale deltas, and long dashes represent the tributary system.

The mean bifurcation angle (μ) of both distributary network populations sampled in this study are consistent with the mathematically predicted $\alpha_{cr} = 72^{\circ}$ (Figure 4.1). Hence, the distributary channel bifurcations in field and laboratory settings are consistent with the hypothesis that their angle is controlled by diffusive flow patterns outside of the channel. Likewise, the mean bifurcation angle measurements are also consistent with the mean angle of tributary network bifurcation measured in DPSR12.

When the bifurcations from the WLD were analyzed as a function of measurement

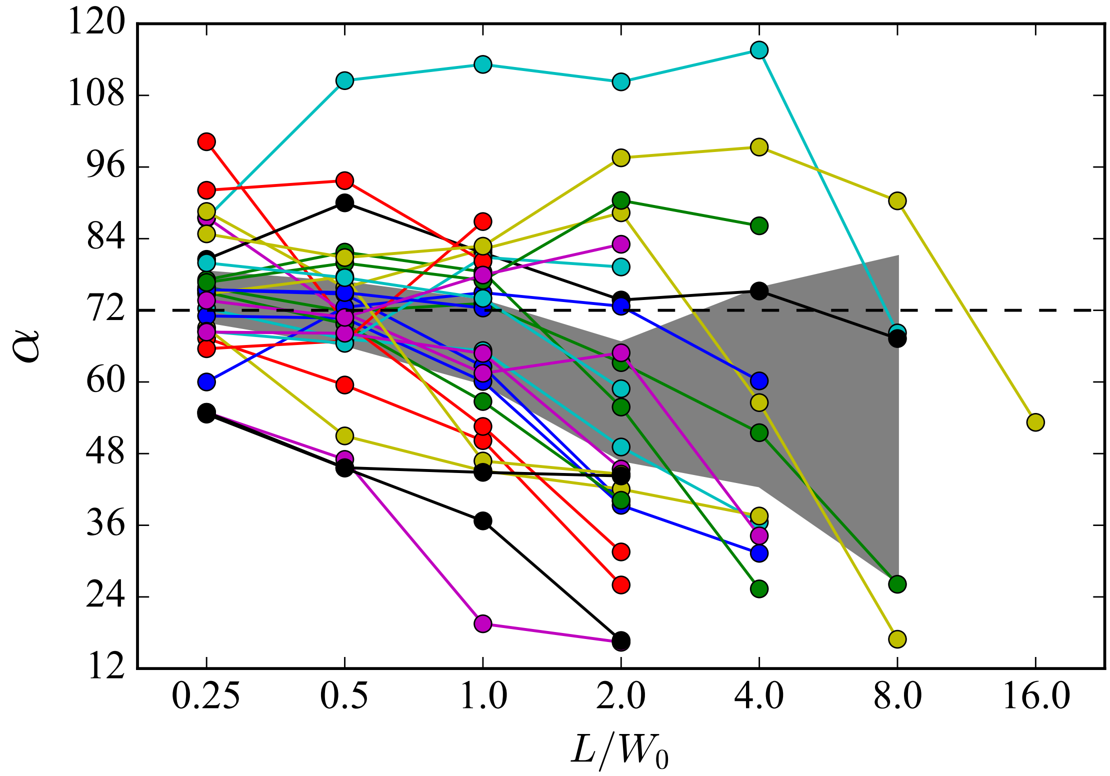

Figure 4.2: **Angle of bifurcation vs. normalized channel length for the WLD.** Dotted line indicates the critical angle of 72°, each colored line represents the progression of a single bifurcation angle moving downstream, and the shaded gray area indicates the 95% confidence interval of the mean bifurcation angle for each increment. The angle of bifurcation generally decreases moving downstream.

Table 4.1: Mean of distribution with 95% confidence interval (μ) and standard deviation (σ) for the bifurcation angles of the deltas measured in this study and the tributary network measured for Devauchelle et al. [2012]. Tests assume a normal distribution.

	Tributaries	Experimental	Field Scale
μ	$71.9^\circ \pm 0.8^\circ$	$68.3^\circ \pm 8.7^\circ$	$70.4^\circ \pm 2.6^\circ$
σ	27.7°	22.3°	18.6°

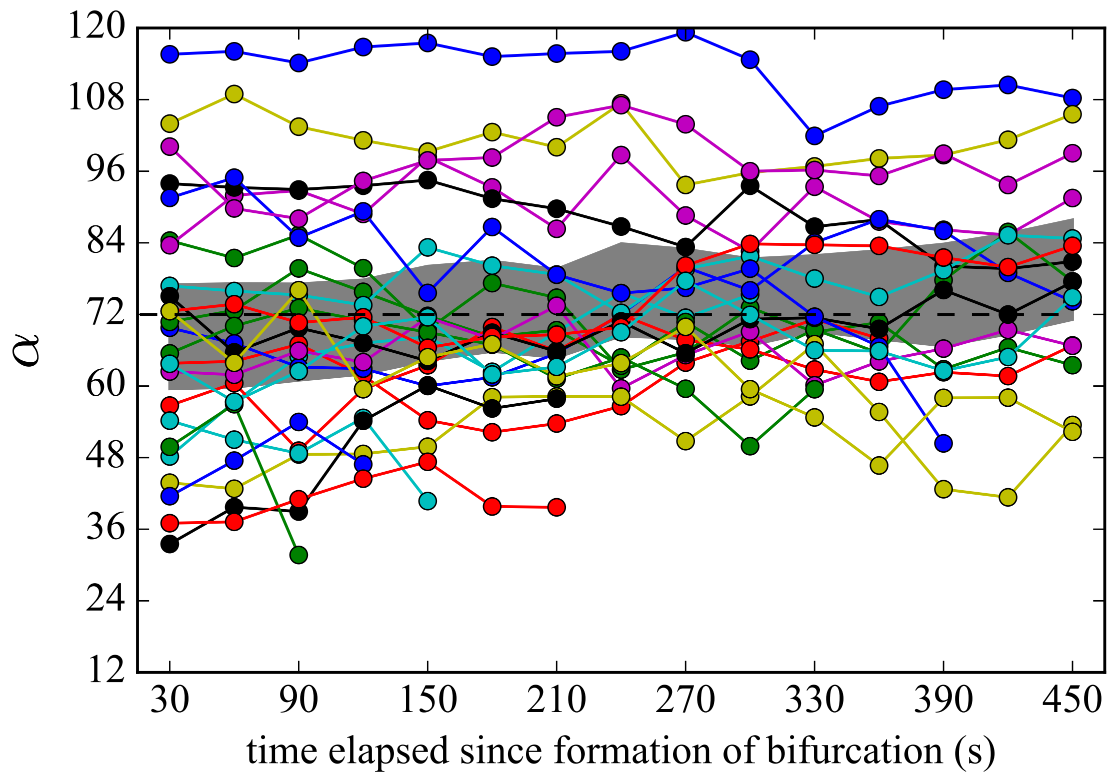

Figure 4.3: **Angle of bifurcation (degrees) vs. time elapsed since formation of bifurcation (seconds).** Data collected from experimental delta WY-9. Dashed black line represents the critical angle of 72°, individual colored lines/points represent a unique bifurcation over time, and the shaded gray area represents the 95% confidence interval for all bifurcation angles at each time increment. The elapsed 450 seconds over which observations were made represents a significant portion of time relative to sediment flux - total sediment added to the basin over this time scale was equal to as much as 50% of the total available volume overlying the delta. All bifurcations were measured at $L/W_0 = 1.0$.

length scale normalized to channel parent channel width (L/W_0), the mean bifurcation angle decreased with increasing L/W_0 (Figure 4.2). Where $L/W_0 \leq 1$, the mean angle was consistent with α_{cr}. However, where $L/W_0 > 1$, the mean bifurcation angle was significantly less than α_{cr} and the 95% confidence interval fell below $72\,^\circ$. Few channel bifurcations could be measured for $L/W_0 > 4$, reducing sample size for particularly long length scales.

Experimental bifurcation angles were measured as a function of time since bifurcation initiation to investigate the temporal evolution of α (Figure 4.3). Individual islands were generally present for less than 450 seconds during the experiment. This represents about half the time required to fill the channel network with sediment, meaning that evolution was measured at significant time scales relative to network construction. While the 95% confidence interval of μ overlapped with α_{cr} for the entire time interval, the range increased slightly over time. Inspection of the data suggest that this increase occurred because individual bifurcations that initiated at less than $72\,^\circ$ either increased over time or were removed due to island erosion or merging. In contrast, bifurcations that initiated with angles greater than $72\,^\circ$ rarely decreased, and they existed for longer periods. Despite this gradual trend in the mean behavior, the standard deviation of α decreased only gradually from 22.25 at 30 s to 17.18 at 450 s.

5 Discussion and Conclusions

The mean bifurcation angle for both experimental and field scale distributary bifurcations is consistent with the critical angle of $72\,^{\circ}$ (Figure 4.1). This previously unexamined aspect of deltaic distributary networks has numerous potential applications. A stratigrapher or reservoir engineer could apply the behavior to predict the location or trajectory of channel bodies in deltaic strata. A coastal engineer could use it to predict future delta growth and flow patterns in either natural or controlled diversion settings, contributing to coastal sustainability efforts [38].

Analysis of 10 field-scale delta systems suggests that both the characteristic angle and the dynamic model are applicable to a wide population of field-scale distributary networks. The assumed exchange of channelized flow and unchannelized flow has only been directly reported from the Wax Lake Delta [31, 32]. However, this process is an underlying assumption to the presence of a critical angle. We therefore expect similar connectivity between channelized and unchannelized regions in the other 10 deltas, and possibly bifurcating deltas in general.

While the mean bifurcation angle is consistent with the theoretical prediction of $72\,^{\circ}$, we noticed that bifurcation angle is dependent upon both length scale and time since island initiation. Measurement of the Wax Lake Delta showed that the α_{cr} test held at small channel-lengths, but as channel length increased, the 95% confidence interval contained a range of values outside of $\alpha_{cr} = 72\,^{\circ}$, and mean angle consistently decreased (Figure 4.2). This indicates that diffusive flow outside of channel networks controls bifurcation dynamics at scales up to the parent channel width. At scales larger than the channel width, other processes appear to have more controlling effect. It has been shown that deltas organize their planform geometry so that the characteristic distance to a channel is a few channel widths [7]. The processes controlling this channel spacing could control the bifurcation angle when measured over these scales. This dependence is similar to seepage channel networks, where bifurcation angle is affected by drainage divides at large length scales [20].

The experimental and field-scale distributary channel bifurcations exhibited significant standard deviations, similar to their tributary counterparts. DPSR12 hypothesized that incipient bifurcations do not initiate at α_{cr}, but grow toward that angle over time [20]. However, analysis of experimental bifurcations through time showed that mean angle was immediately consistent with α_{cr}, yet the standard deviation of μ decreased by only 23% over half the channel network filling time-scale. Hence, bifurcations appear to initiate from a distribution centered at α_{cr}, and α_{cr} appears to be a weak attractor of bifurcation angle at best in distributary systems. The gradual increase in μ suggests that the bifurcation may even be more consistent at initiation than over very long timescales. An explanation for the continued angle variability within the system may involve the effect of additional processes on α_{cr}, such as discharge asymmetry between the daughter channels. An additional explanation for the variance in bifurcation angle could be flow interference preventing the initiation and maintenance of the inter-distributary flow network; this could be caused by physical blockages, such as vegetation, or by variable channel discharge preventing inundation of the inter-distributary bay.

Numerous conditions exist where this theory would likely not apply. In river deltas with intermittent water flow, the inter-distributary bay might not be sufficiently saturated with water, meaning that connectivity might not exist between the channel and inter-distributary and the flow patterns therefore would not form a diffusive network. This especially applies to inland deltas where bankfull flow might only exist seasonally. River deltas in especially polar regions could also not satisfy the prerequisite assumptions for this theory. The inter-distributary bay generally displays lower flow velocities than the primary channel, meaning that the resident water could form ice, preventing the flow patterns from forming an interconnected diffusive network. Interestingly, the dataset in this paper does contain two river deltas that are vulnerable to freezing, the Mossy delta in Canada and the Pechora delta in Russia.

Potential settings where the characteristic bifurcation angle could theoretically $= 72^\circ$ include subaqueous tide-dominated delta deposits and intrachannel chevron-shaped deposits in fluvial systems. Both of these are depositional features that divide (e.g. bifurcate) the bulk flow in a channelized system, with shallow lower velocity flow moving over the depositional feature as deposition occurs. Similar characteristic angles should exist for these features, after accounting for appropriate constraining conditions and underlying assumptions.

The characteristic angle of bifurcation for distributary channel networks could be applied to the subsurface in order to better understand deltaic deposits in the rock record. River deltas deposit massive amounts of sediment which can act as reservoirs/source rocks for hydrocarbons or as aquifers for water. The ability to predict the planform geometry of a deltaic deposit in the subsurface could aid geologists in facies interpretation, allowing for more efficient placement of wells. However, this characteristic behavior has not yet been tested against interpreted distributary channel networks in the rock record.

Deltaic distributary networks are not completely analogous to tributary river networks. For example, the nested drainage basin morphology in tributary systems is not

Figure 5.1: **Mid-channel depositional feature found in the inland region of the Ganges River.** These chevron- and diamond-shaped features are commonplace in the basinward portions of the Ganges and other large scale fluvial systems. Theoretically they should form a characteristic angle of 72°. (Source: Google Earth)

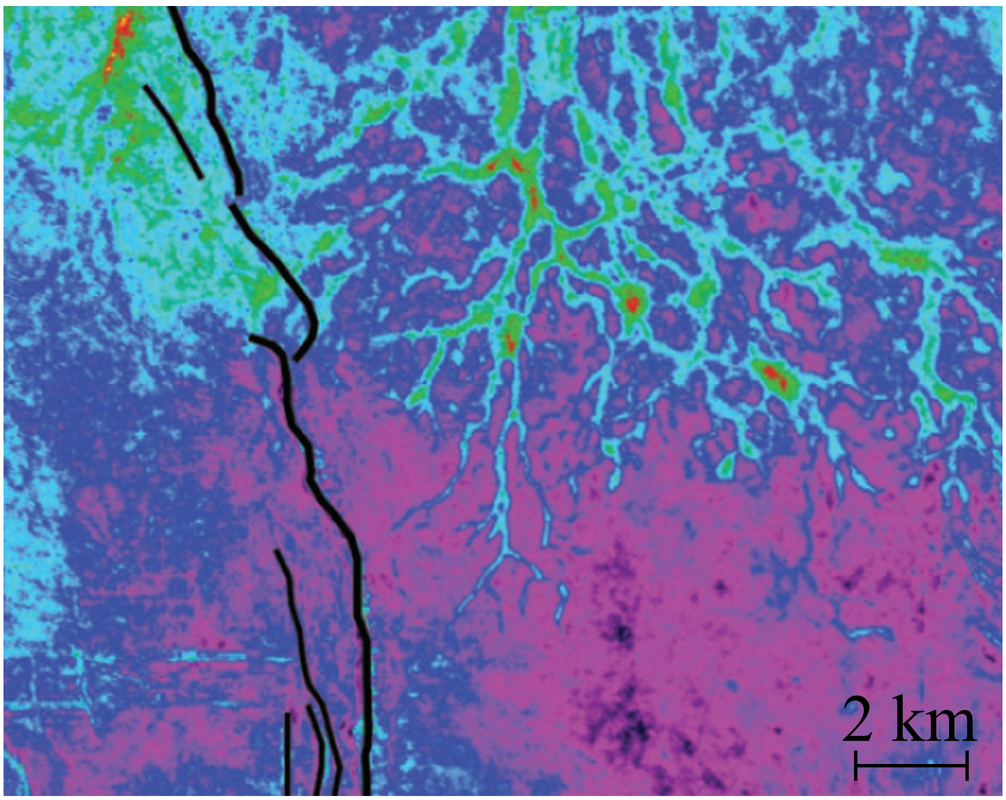

Figure 5.2: **Subsurface seismic image interpreted as a river delta [39].** The Qingshankou Formation in China is believed to have been deposited as deltaic sediment in a shallow, gently dipping basin. The amplitude features interpreted as distributary channels could be measured and tested to see if this subsurface network is congruous with the characteristic angle of 72°. The Qingshankou Formation has acted as a reservoir for a significant amount of hydrocarbons, highlighting the importance of a better understanding of these features.

possible in a delta where all flow must eventually travel across the delta and into the receiving basin [31]. Further, while the morphology of tributary networks is scale invariant over many orders of magnitude [40], there are several aspects of deltas that are not scale invariant [7]. Despite these differences, the critical angle of 72° found on deltas suggests that this aspect of distributary channel network morphology is controlled by extra-channel flow patterns, similar to groundwater seepage tributary channel networks. In essence, the direction of flow through the bifurcation and in the surrounding unchannelized regions does not matter. This contrasts with established distributary network theory, which predicts bifurcation formation as a function of hydrodynamics within channels or at channel termini [24, 25, 26]. Intra-channel and extra-channel dynamics are not necessarily mutually exclusive because they are used to predict different aspects of the network (distance between bifurcations and bifurcation angle, respectively). However, the emergence of a critical angle based on simplified unchannelized flow patterns suggests that extra-channel flow is also involved in the initiation of a bifurcated channel network. Continued examination of the relationship between delta channel network dynamics and extra-channel flow patterns may yield further insight into delta depositional patterns, and also provide a new analogue for studies of tributary networks.

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